(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: **0 284 250 A2**

(12) **EUROPEAN PATENT APPLICATION**

(21) Application number: **88302130.5**

(51) Int. Cl.⁴: **G01N 9/00**

(22) Date of filing: **11.03.88**

(30) Priority: **27.03.87 US 31850**

(43) Date of publication of application: **28.09.88 Bulletin 88/39**

(84) Designated Contracting States: **DE FR GB IT**

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(54) **Apparatus for use with a densitometer.**

(57) Apparatus for use with a densitometer having a probe (4) with an output and a probe driver (18) for driving the probe includes a loop circuit coupled between the probe output and the probe driver. An amplifying circuit (12) is coupled in the loop circuit to amplify the signal provided by the probe (4). A phase/gain control device (16) is also coupled in the loop circuit between the amplifying device (12) and the probe driver (18). The phase/gain control device (16) controls the loop circuit to provide a loop gain of at least one and a substantially zero degree phase shift between the probe driver (18) and the probe output signal. The amplifying device includes an op-amp which is preferably coupled to a shielded cable (14) carrying the probe output signal. The shield conductor and one input of the op-amp are held at ground potential, and the op-amp acts to hold the centre conductor at ground potential also. With the centre conductor held at ground potential, the output signal from the probe varies with current, not voltage. A resistance in the feedback path of the op-amp converts current changes to voltage changes proportional to the output signal of the probe. Since the centre conductor of the shielded cable varies in current only, the output signal from the probe is insensitive to cable length, cable loading, and cable capacitance.

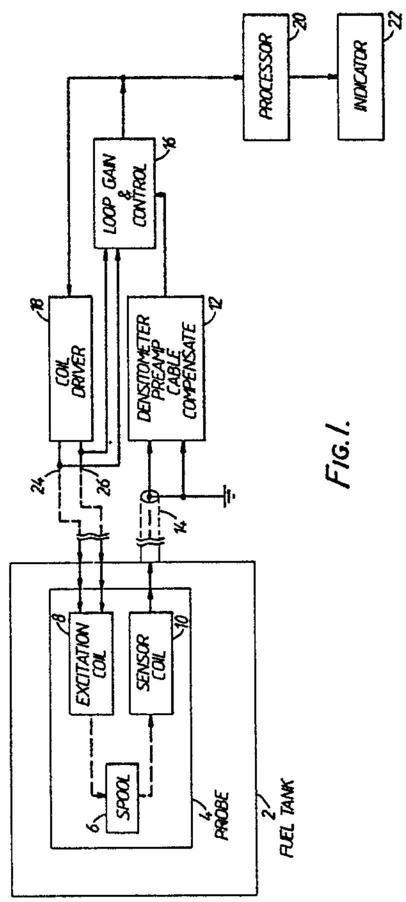


FIG. 1.

EP 0 284 250 A2

APPARATUS FOR USE WITH A DENSITOMETER

The present invention relates to apparatus for use with a density sensor or densitometer and more particularly to a vibrating spool densitometer such as used to determine the density of a fluid in a tank, for example an aircraft fuel tank. One example of a vibrating spool densitometer embodying the invention has an output signal which is dependent only upon the fluid in which the sensor is immersed, and is not dependent upon the length, shielding, or capacitive loading of the cable which connects the densitometer to an indicator.

Vibrating spool densitometers are known for determining the density of a fluid in a tank. Such densitometers are particularly useful in an aircraft fuel tank for providing fuel status to the pilot. Basically, a vibrating spool densitometer comprises a probe inserted into the fuel tank, and an interface for coupling the probe output signal to a processor which provides an appropriate indication to the pilot. The probe includes a vibrating vane or spool which is stimulated by a spool driver to vibrate at resonance. A pickup coil or crystal picks up vibrations from the tank and provides an output signal containing information about the density of fluid in the tank.

In the prior art, an interface unit for the vibrating spool density sensor was provided near the fuel tank to receive the probe output signal and condition it for transmittal to a processor. However, such interface units are extremely sensitive to cable capacitance which thus precludes the use of protective shielding cable. Furthermore, the sensitivity to cable capacitance required the interface unit to be located within 20 feet of the density sensor. Typically, a separate electronic interface unit was mounted near the fuel tank containing the sensor. On a large aircraft, as many as six fuel tanks were used, thus requiring six electronic interface units. The number and location of such interface units obviously increased the aircract weight and diminished reliability. Such prior art densitometers are disclosed, inter alia, in US-PS 4 546 641 (Nguyen). Since the output of sensor 14 therein comprises two separate lead lines, preamplifier 16 must be located near the fuel tank.

Likewise, a known densitometer is disclosed in US-PS 4 495 818 (Ikeda et al). In Figure 5, Ikeda et al discloses an electrical circuit for vibrating the vibrator 1 at its resonant frequency. Amplifier U4 is used to rotate the phase of the output signal from the limiter to satisfy the condition for self-oscillation.

However, the device of Ikeda et al is directed to the physical construction of the pressure transducer, and also must include an interface unit coupled near the fuel tank.

Finally, US-PS 4 215 566 (Ghahramani) discloses a vibration densitometer having a magnetostrictive drive with a coil and a crystal pickup. A loop circuit including an driver amplifier provides the coil with a voltage twice that ordinarily provided. However, Ghahramani also requires an interface unit coupled in proximity to the fuel tank.

Such known vibrating densitometer interface units were required to provide the oscillator with components necessary for generation of a frequency for processing by an appropriate fuel tank signal conditioner. The remote signal conditioner was required because of the characteristics of the densitometer, the interface electronics, and the interconnecting cable. Thus, known vibration densitometers require additional electronic units, thereby increasing the cost, complexity, weight, and reliability risk of the aircraft.

According to the invention, there is provided apparatus for use with a densitometer having a probe with an output, and a probe driver coupled to said probe, characterised by a loop circuit coupled between said probe output and said probe driver; amplifying means , coupled in said loop circuit, for amplifying a signal provided on said probe output with a phase shift independent of the length or capacitance loading of said probe output, and phase/gain control means, coupled in said loop circuit between said amplifying means and said probe driver, for controlling said loop circuit to provide a loop gain of at least one and a substantially zero degree phase shift between said probe drive and said probe output signal.

According to the invention, there is also provided apparatus for use with a densitometer having a probe with an output and a probe driver coupled to said probe characterised by cable means, coupled to said probe output, for carrying an output signal from said probe , and amplifier-phase/gain control means, coupled between said cable means and said probe driver, for amplifying said probe output signal independently of the length or capacitance loading of said cable means.

According to the invention, there is further provided apparatus for use with a densitometer having a probe with first and second inputs and an output, characterised by shielded cable means having first and second conductors for carrying a signal from said probe output; a loop circuit coupling said shielded cable means to said probe inputs; and amplifier-phase/gain control means coupled in said loop circuit, for providing said loop circuit with a gain factor of at least one, and for providing a substantially zero degree phase shift between said probe output and inputs, and for holding said probe output signal at ground potential.

Apparatus according to the invention for use with a vibrating spool densitometer, and a vibrating spool densitometer embodying the invention, will now be described, by way of example, with reference to the accompanying drawings in which:

Figure 1 is a block diagram of the densitometer; and

Figure 2 is a detailed schematic of the densitometer;

The densitometer to be described allows a densitometer sensor to be located in a fuel tank with no active electronics associated with the densitometer in the tank hardware. The required signal conditioning for the densitometer sensor is located in an electronics package which does not have to be located near the fuel tank.

The densitometer is designed with a view toward keeping the probe output signal immune to cabling effects. The densitometer requires no problem wiring coaxial or shielded cable to interconnect the density sensor with the appropriate signal conditioning electronics package. The design of the electronics also limits tank energy to less than 0.1 microjoules, and the current to less than 10 milliamperes. These current and energy levels are intrinsically safe.

The electronics package for the densitometer may be supplied with appropriate driving voltage (typically 28 volts DC for an aircraft) from the appropriate fuel quantity channel. Internal circuitry sustains densitometer spool vibration (which relates to fuel density) and the sine wave output of the electronics package is sent to a processor unit. Calibration constants for the densitometer may be carried as resistors in a potted area behing the densitometer sensor. The resistor values are read by a processing unit, so that a densitometer frequency output can be converted directly into fuel density. The calibration values are carried on each density sensor; therefore, the densitometer may be replaced as required without affecting system calibration and without any calibration data entry required by aircraft maintenance personnel.

There is no need to do anything to the electronics package if a densitometer is replaced, and no need to do anything to the densitometer if the electronics package is replaced. The design of the densitometer also allows its signal conditioning circuitry to be placed on the same processor electronics package that measures the fuel tank quantity, thus eliminating the additional interface electronics package required by known vibration densitometers.

Since the densitometer provides for signal conditioning which is not sensitive to cabling effects, a number of advantages accrue, such as increased system reliability, easier installation, lower weight, and lower cost.

In Figure 1, fuel tank 2 includes a probe 4 which may comprise a vibrating spool 6 given by an excitation device, for example an excitation coil 8. Sensor coil 10 picks up spool vibrations and provides a probe output signal which is output from fuel tank 2. A variety of alternative sensors may be provided, such as a crystal.

The probe output signal from sensor coil 10 is provided to a densitometer preamplifier cable compensation circuit 12 via cabling 14. It is particularly preferred that cable 14 comprise a coaxial cable, or any other known shielded cabling suitable for such use. The shielding conductor of cable 14 is coupled to ground, for reasons described later herein. The shielded conductor is also coupled to the densitometer preamplifier circuit 12, as is the signal conductor of cable 14.

Densitometer preamplifier 12 is an important part of the densitometer. It allows the signal from the sensor coil 10 to be amplified with a phase shift independent of the length of capacitance loading of the cable connecting the densitometer to the densitometer preamplifier 12. In order for the sensor to operate properly, the phase of the signal from the sensor coil 10 must be carefully controlled. An uncontrolled phase shift will cause the sensor to stop vibrating, resulting in a loss of signal. Previous methods of signal conditioning required the sensor to be located close to the electronics signal conditioning package to avoid such phase shifts. Densitometer preamplifier 12 makes the system relatively insensitive to cabling effects, thus allowing the densitometer preamplifier 12 to be located in any convenient location.

The amplifier signal from densitometer 30 preamplifier 12 is applied to a loop gain and control circuit 16.

Loop gain and control circuit 16 provides an input to coil driver 18 and also samples the output signals from coil driver 18.

Loop gain and control circuit 16 is configured to ensure a substantially zero degree phase shift between the sensor coil output signal and the coil driver output signal. The densitometer operates with a resonant element sensor. At the frequencies of interest, the sensor has a gain peak and a phase of zero degrees between the input (coil driver 18) and the output (sensor coil 10). In order to sustain oscillation of the vane at the resonant frequency, loop gain and control circuit 16 must provide a loop of at least one, and a phase shift of zero gain degrees. The conditions required to sustain oscillation are well known to anyone versed in the art. Loop gain and control section 16 monitors the outputs of coil driver 18 and adjusts the loop gain such that spool oscillations are just sustained. Any phase errors in the loop circuit are detected and corrected beforehand by making part substitutions in the loop gain and control circuit, as described later herein.

The loop gain and control circuit 16 provides an output signal which corresponds to the density of the fuel in fuel tank 2. This output signal may be provided to a processor 20 which may provide a fuel density indication on indicator 22. As above indicated, the output signal from loop gain and control circuit 16 is also applied to coil driver 18 which, in turn, drives excitation coil 8 to provide appropriate vibration to vane 6.

Coil driver 18 provides enough power gain for the output of the loop gain and control circuit 16 to drive the excitation coil 8. Coil driver 18 also provides a fixed gain of approximately 11 to help make up for losses in probe 4. Furthermore, coil driver 18 provides a balanced output to minimize interference with other systems and also provides a low pass filter characteristic which prevents the excitation of resonant frequencies outside the range of interest. The output impedance of coil driver 18 is low so that cable loading effects will not affect the system operation.

Both the densitometer preamplifier cable compensation circuit 12 and coil driver 18 may be 15 located remotely from the fuel tank 2. This is because the output signal of sensor coil 10 is relatively immune to degradation due to cabling effects.

Figure 2 illustrates more details of the presently preferred embodiment. The output signal from sensor coil 10 is provided to densitometer preamplifier 12 through cable 14. The centre conductor of cable 14 is preferably connected to the inverting input of an operational amplifier U1 through a summing junction 17. The shielded conductor of cable 14 is coupled to both the noninverting input of U1 and to ground.

Since the operation of op-amp U1 is to keep summing junction 16 at the same potential as the noninverting input, and since the noninverting input is kept at ground potential, the net result is that the centre conductor of cable 14 carrying the probe output signal is held at ground potential. With the centre conductor at ground potential, there is no voltage across any stray resistance or capacitance to ground on the return wire from sensor coil 10. Since there is no voltage across these stray elements, no current flows through them. With no current flow, the cable strays cannot affect the system phase or gain. Thus, the system is independent of cabling effects, and the cable can be made as long as desired.

With the centre conductor of cable 14 held at ground potential, the output signal from sensor coil 10 is a current. Thus, the probe output signal carried on cable 14 is current-varying and not voltage-varying. The feedback action of the op-amp U1 causes the input current to flow through feedback resistor R1. Current in resistor R1 results in an output voltage proportional to the input current provided by the sensor coil 10. Thus, the voltage invariant probe output signal carried on cable 14 is converted to a voltage-varying signal at the output of preamplifier 12. Therefore, an effective measure of the density of fuel in fuel tank 2 may be provided without regard to the effects or length of cabling 14.

Op-amp U1 amplifies the output signal from probe 4 with a phase shift relatively independent of a length or capacitance loading of the probe output cable 14. This is because op-amp U1 has a low source impedance. Therefore the capacitance load on the probe output cable 14 does not change the phase. Thus, the length and capacitance loading of the cable output 14 does not affect the phase of the signal provided at the output of preamplifier 12.

The output of op-amp U1 is provided to loop gain and control circuit 16. Preferably, loop gain and control circuit 16 comprises two variable gain stages composed of amplifiers U2 and U3 for controlling the loop gain.

Both stages are identical and comprise a feedback loop in the form of a T attenuator which controls gain. The ground leg of the T is partially formed by the drain-source leg of a JFET transistor (Q1 and Q2). By changing the gate voltage of the JFET transistor, the drain source resistance is modulated, thus forming a voltage-controlled T attenuator which controls gain. The gate voltage for each JFET transistor Q1 and Q2 is derived by amplifier U7, which samples the drive signals provided by coil driver 18 to the excitation coil 8. These signals are rectified by diode CR 1 and low passed filtered by capacitor C11 and resistor R29 to give a DC signal proportional to the sense coil drive. If there is no signal present at the output, the DC voltage is zero, which modulates the drain-source resistance of transistors Q1 and Q2 to a minimum value, and sets the loop gain to a maximum. As oscillations build up in the closed resonant system, the DC voltage on the gates of transistors 01 and 02 goes negative, causing an increase in drain-source resistance, and a decrease in the gain of amplifiers U2 and U3. The gain stabilizes at a value such that the drive to the sense coil is approximately 1 volt peak-to-peak.

The phase of the circuit is preadjusted by component selection at installation of the densitometer equipment. Briefly, the circuit is tuned depending upon the particular amplifiers used in preamplifier 12, loop gain and control circuit 16 and coil driver 18. In Figure 2, capacitor C2 may be specially preselected in order to control the phase of the circuit. Capacitor C2 can be chosen by taking the loop circuit output and plotting phase versus frequency. Then, capacitor C2 is selected to ensure a substantially zero degree phase shift in the loop circuit. Changes in capacitors C3 and C7 in coil driver 18 may also affect the phase of the circuit. Again, empirically tuning the circuit may require substitutions in capacitors C3 and C7. Thus, the densitometer can be pre-tuned by part substitution with the amplifiers or capacitors of the loop gain and control circuit 16 and coil driver 18. All such part substitutions are to be included within the scope of the appended claims.

The output of loop gain and control circuit 16 is provided in sensor coil driver 18 to a balanced output driver U5 which provides a positive drive output on line 24 to excitation coil 8 and amplifier U7. The output signal of loop gain and control circuit 16 is also applied in parallel to a unity gain inverter stage U4 which provides an inverted signal output to standard active filter U6. Driver U6 develops on line 26 the negative phase of the balanced drive output to excitation coil 8 and amplifier U7. Both balanced output drivers U5 and U6 are standard active filters configured as 3dB Chebyshev low pass filters. The filtered output signals from filters U5 and U6 are returned to excitation coil 8 which then properly drives vane 6 at resonance.

While the circuit of Figure 2 is a detailed schematic of a preferred embodiment, those of skill in this field will readily appreciate that many alternative circuits may be designed depending upon the particular use to which the sensor probe is put. All such alternative circuits are to be included within the scope of protection afforded to the present invention.

Thus, what has been described is densitometer apparatus for making the probe output signal immune to cabling effects, thereby allowing signal conditioning circuitry to be located remotely from the sensor probe. Where a plurality of probes are utilized in a single system, appropriate signal conditioning circuitry may be unified in one package, for example, co-located with processor and indicator devices.

The densitometer described overcomes advantages of known vibration densitometers by eliminating the need for interface units located at each fuel tank. The densitometer provides a means of signal conditioning a vibrating spool densitometer signal in such a fashion that the vibration frequency of the densitometer is dependent only upon the fluid in which the sensor is immersed, and is not dependent upon the length, shielding or capacitive loading of the interconnection cable. Therefore, the interconnection cable may now be shielded. This further protects the system from influences of high energy fields, for example, RF interference.

Since the output signal of the vibration densitometer is independent of the length of cabling, the signal condition circuitry which transmits the probe output signal to the appropriate processor may now be located at any desired location in an aircraft, thus eliminating extra electronic packages. In fact, the signal conditioning circuitry may now be located at the processor location itself.

While the present invention has been described in connection with what is presently considered to be the most practical and preferred embodiment, it is to be understood that the invention is not to be limited to the disclosed embodiment. On the contrary, the present invention is intended to cover various modifications and equivalent arrangements included within the spirit and scope of the appended claims, which scope is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures.

Claims

1. Apparatus for use with a densitometer having a probe (4) with an output, and a probe driver (18) coupled to said probe (4), characterised by a loop circuit (12,16) coupled between said probe output and said probe driver (18); amplifying means (12), coupled in said loop circuit, for amplifying a signal provided on said probe output with a phase shift independent of the length or capacitance loading of said probe output, and phase/gain control means (16), coupled in said loop circuit between said amplifying means (12) and said probe driver (18), for controlling said loop circuit to provide a loop gain of at least one and a substantially zero degree phase shift between said probe drive and said probe output signal.

2. Apparatus according to claim 1, characterised in that said probe output comprises a cable (14) having a signal conductor and a shield conductor, and wherein said amplifying means (12) includes means for holding said signal conductor at ground potential.

3. Apparatus according to claim 1 or 2, characterised wherein said probe output carries an output signal, and wherein said amplifying means (12) includes means for making said probe output signal a current-varying signal.

4. Apparatus according to any preceding claim, characterised in that said probe output is a shielded cable (14) having a shield conductor and a signal conductor, and wherein said amplifying means (12) comprises an operational amplifier (U1) having first and second inputs, said first input being coupled to said signal conductor, and said

second input and said shield conductor being coupled to ground to hold said signal conductor at ground potential.

5. Apparatus according to claim 4, characterised in that said operational amplifier (U1) includes a summing junction coupled between said signal conductor and said first input, said summing junction being coupled to an output of said operational amplifier to cause said signal conductor to be held at ground potential to make said probe output signal an invariant voltage.

6. Apparatus according to claim 5, characterised in that said operational amplifier (U1) includes a resistance (R1) coupled between said summing junction and said operational amplifier output to convert said invariant voltage to a varying voltage signal.

7. Apparatus according to any preceding claim, characterised in that said phase/gain control means includes first (U2) and second (U3) variable gain stages coupled in series between said amplifying means (12) and said probe driver (18) for providing said loop gain.

8. Apparatus according to claim 7, characterised in that each of said first and second variable gain stages comprises a T attenuator feedback loop (R3 to R5; R6 to R8) having a grounded leg including a transistor (Q1;Q2) for adjusting said loop gain.

9. Apparatus according to claim 8, characterised in that said first and second variable gain stages respectively comprise first and second amplifiers (U2;U3) having said feedback loops respectively, said first amplifier (U2) having an input coupled to said amplifying means (12) and an output, said second amplifier (U3) having an input coupled to said first amplifier output (U2) and an output coupled to said probe driver (18).

10. Apparatus according to claim 8 or 9, characterised in that said phase/gain control means includes a third amplifier (U7) coupled to said probe driver (18), for controlling a gate voltage of both said attenuator feedback loop transistors (Q1;Q2) to control said loop gain.

11. Apparatus for use with a densitometer having a probe (4) with an output and a probe driver (18) coupled to said probe (4), characterised by cable means (14), coupled to said probe output, for carrying an output signal from said probe (4), and amplifier-phase/gain control means (12,16), coupled between said cable means (14) and said probe driver (18), for amplifying said probe output signal independently of the length or capacitance loading of said cable means (14).

12. Apparatus according to claim 11, characterised in that said cable means includes first and second conductors, and in that said amplifier-phase/gain control means includes an op-amp (U1) having a first input coupled to said first conductor and a second input coupled to ground and said second conductor to hold said first conductor at groúnd potential so that said output signal is voltage invariant.

13. Apparatus according to claim 12, characterised in that said op-amp (U1) includes an output and a feedback path coupled between said op-amp output and said first conductor to cause said first conductor to be held at ground potential.

14. Apparatus according to claim 13, characterised in that said feedback path includes a capacitance (C1) and a resistance (R1) coupled in parallel to convert said voltage invariant signal into a voltage varying output.

15. Apparatus for use with a densitometer having a probe (4) with first and second inputs (24,26) and an output, characterised by shielded cable means (14) having first and second conductors for carrying a signal from said probe output; a loop circuit (12,16) coupling said shielded cable means (14) to said probe inputs; and amplifier-phase/gain control means (12,16) coupled in said loop circuit, for providing said loop circuit with a gain factor of at least one, and for providing a substantially zero degree phase shift between said probe output and inputs, and for holding said probe output signal at ground potential.

16. Apparatus according to claim 15, characterised in that said amplifier-phase/gain control means includes an op-amp (U1) having an output, a feedback path, a first input coupled to said first conductor, and a second input coupled to said second conductor and ground to cause said probe signal to be held at ground potential and to vary in current.

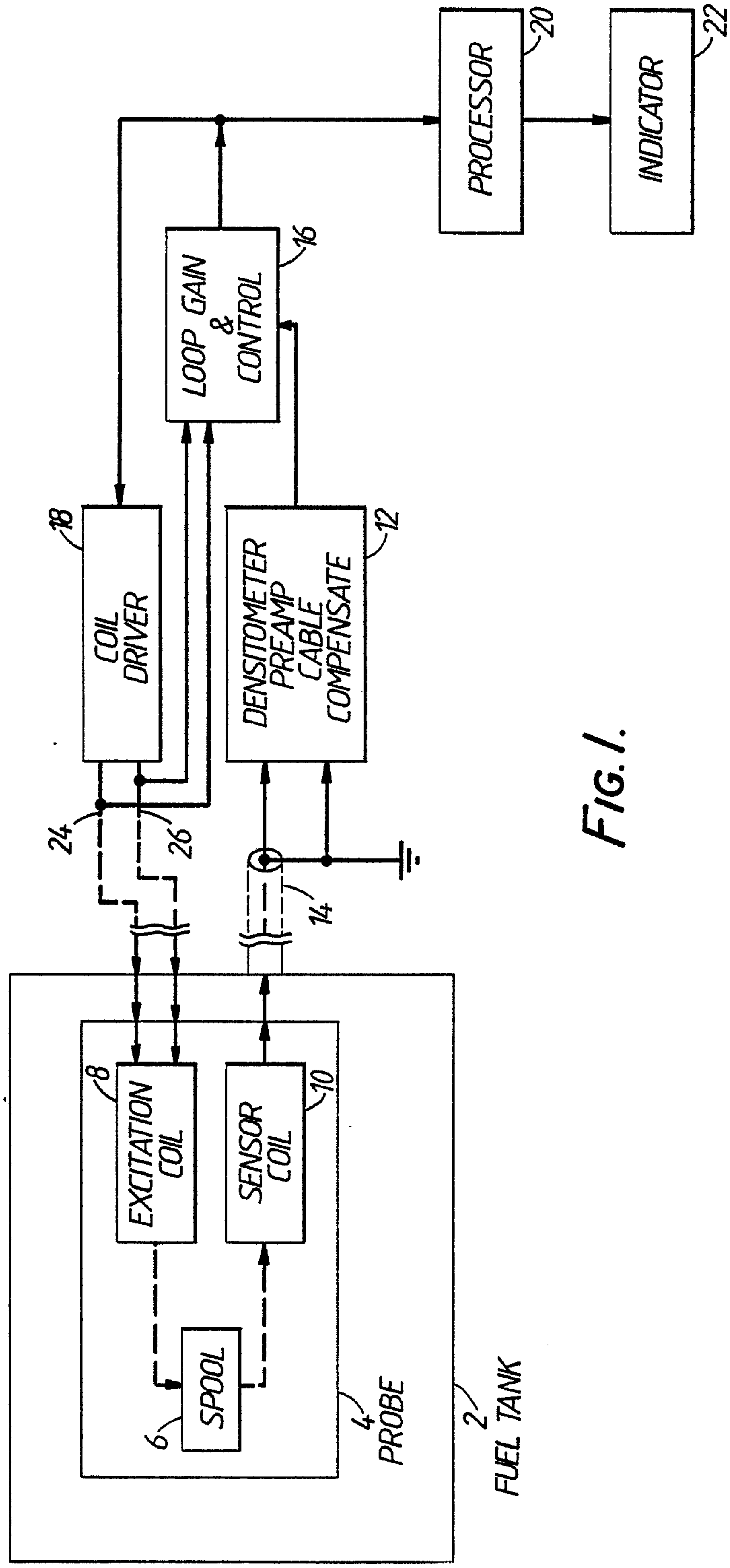
17. Apparatus according to claim 16, in that said feedback path includes means for changing the current varying probe signal into a voltage varying signal.

18. Apparatus according to claim 15, characterised in that said amplifier-phase/gain control means includes an op-amp (U1) having a first input coupled to said first conductor, a second input coupled to said second conductor and to ground to hold said probe signal at ground potentia an output, and a feedback path (R1,C1) coupled between said op-amp first input and output, the feedback path including a resistance (R1) coupled therein to convert said ground potential probe signal to a voltage-varying signal.

19. Apparatus according to any one of claims 15 to 18, characterised by probe drive means (18) for driving said probe, said probe drive means having an input coupled to an output of said amplifier-phase/gain control means (12,16) and first and second outputs respectively coupled to said probe first and second inputs (24,26).

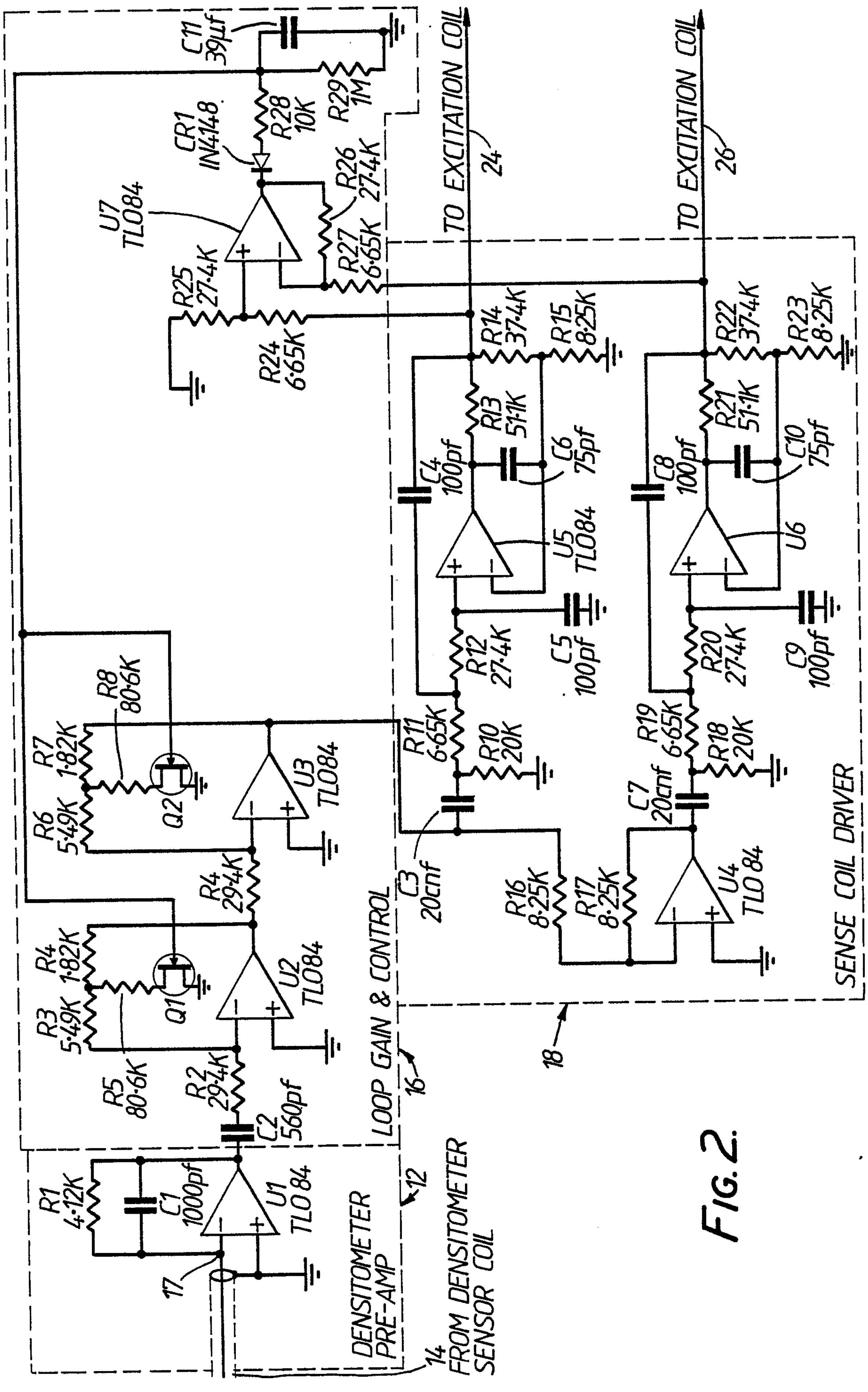
20. Apparatus according to any one of claims 15 to 19, characterised in that said amplifier-phase/gain control means includes: a first amplifier (U2) having an input coupled to said op-amp (U1) output, a first feedback path (R3 to R5), and an output; a second amplifier (U3) having an input coupled to said first amplifier (U1) output, a second feedback path (R6 to R8), and an output coupled to said probe driver means (18); and a third amplifier (U7), having first and second inputs respectively coupled to said probe driver first and second outputs (24,26), and an output coupled to said first and second feedback paths (R3 to R5, Q1; R6 to R8; Q2) for controlling said loop gain.

21. Apparatus according to any one of claims 15 to 20, characterised in that said probe driver means includes: unity gain inverter means (U4) for inverting a gain of said amplifier-phase/gain control means (12,16) output; first low pass filter means (U5), coupled to said amplifier-phase/gain control means output, for providing a positive drive output to said probe driver first output (24); and second low pass filter means (U6), coupled to said unity gain inverter, for providing a negative drive output to said probe driver second output (26).



PROCESSOR
20
INDICATOR
22
LOOP GAIN & CONTROL
16
COIL DRIVER
18
DENSITOMETER PREAMP CABLE COMPENSATE
12
24
26
14
EXCITATION COIL
8
SENSOR COIL
10
SPOOL
6
4 PROBE
2 FUEL TANK

FIG. 1.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39µf
R28
10K
R29
1M
CR1
IN4148
R26
27·4K
U7
TL084
R27
6·65K
R25
27·4K
R24
6·65K
TO EXCITATION COIL
24
TO EXCITATION COIL
26
R14
37·4K
R15
8·25K
R22
37·4K
R23
8·25K
R13
51·1K
C4
100pf
C6
75pf
R21
51·1K
C8
100pf
C10
75pf
U5
TL084
U6
C5
100pf
C9
100pf
R12
27·4K
R20
27·4K
R8
80·6K
R7
1·82K
R6
5·49K
Q2
U3
TL084
R11
6·65K
R10
20K
R19
6·65K
R18
20K
C7
20cnf
C3
20cnf
R4
29·4K
R16
8·25K
R17
8·25K
U4
TL0 84
R4
1·82K
R3
5·49K
Q1
U2
TL084
SENSE COIL DRIVER
LOOP GAIN & CONTROL
16
18
R5
80·6K
R2
29·4K
C2
560pf
12
R1
4·12K
C1
1000pf
U1
TL0 84
17
DENSITOMETER
PRE-AMP
14
FROM DENSITOMETER
SENSOR COIL

FIG. 2